

Fluid-like dissipation of magnetic turbulence at electron scales in the solar wind

O. Alexandrova,* C. Lacombe, and A. Mangeney
 LESIA-Observatoire de Paris, CNRS, UPMC Université Paris 06,
 Université Paris-Diderot, 5 place J. Janssen, 92190 Meudon, France.

R. Grappin
 LUTH-Observatoire de Paris, CNRS, Université Paris-Diderot, 5 place J. Janssen,
 92190 Meudon, France & LPP, Ecole Polytechnique 91128 Palaiseau, France.

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The turbulent spectrum of magnetic fluctuations in the solar wind displays a spectral break at ion characteristic scales. At electron scales the spectral shape is not yet completely established. Here, we perform a statistical study of 102 spectra at plasma kinetic scales, measured by the Cluster/STAFF instrument in the free solar wind. We show that the magnetic spectrum in the high frequency range, [1, 400] Hz, has a form similar to what is found in hydrodynamics in the dissipation range $\sim Ak^{-\alpha} \exp(-k\ell_d)$. The dissipation scale ℓ_d is found to be correlated with the electron Larmor radius ρ_e . The spectral index α varies in the range [2.2, 2.9] and is anti-correlated with ℓ_d , as expected in the case of the balance between the energy injection and the energy dissipation. The coefficient A is found to be proportional to the ion temperature anisotropy, suggesting that local ion instabilities may play some rôle for the solar wind turbulence at plasma kinetic scales. The exponential spectral shape found here indicates that the effective dissipation of magnetic fluctuations in the solar wind has a wave number dependence similar to that of the resistive term in collisional fluids $\sim \Delta\delta B \sim k^2\delta B$.

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In ordinary fluids, turbulent fluctuations are unpredictable, but their statistics are predictable and universal [1]; turbulent spectra follow the power-law $\sim k^{-5/3}$ for any local conditions (k being the wave number). This empirical result was explained by Kolmogorov [2] assuming self similarity of turbulent fluctuations between the energy injection scale (the largest scale of the system) and the dissipation one ℓ_d (the smallest scale).

In the magnetized solar wind, collisions are very rare (the mean free path is of the order of 1 AU), the dissipation process at work and the characteristic dissipation length are not known precisely. Moreover, in a magnetized plasma, it is difficult to imagine self-similarity at all scales where turbulent fluctuations are observed, since there exist several spatial and temporal characteristic scales, such as the ion Larmor radius $\rho_i = \sqrt{2kT_{i\perp}/m_i}/(2\pi f_{ci})$, the ion inertia length $\lambda_i = c/\omega_{pi}$, the corresponding electron scales ρ_e, λ_e , and the ion and electron cyclotron frequencies f_{ci}, f_{ce} . At these scales, the dominant physical processes change, which affects the scaling of the energy transfer time and furthermore the energy transfer rate, leading to spectral shape changes.

In this Letter we study magnetic field turbulent fluctuations at plasma kinetic scales, starting at ion scales and going beyond electron spatial scales.

The broad solar wind spectra ranging from magneto-hydrodynamic scales (MHD) to electron scales have been

recently studied in [3, 4]. In a restricted statistical study of 7 time intervals under different plasma conditions, Alexandrova et al. [3] show that the spectrum appears as quasi-universal when the Kolmogorov's normalization is used (see e.g. [1]). In ordinary fluids, the Kolmogorov universal function is $E(k)\ell_d/\eta^2 = (k\ell_d)^{-5/3}$, with η being the kinematic viscosity and ℓ_d the dissipation scale. In our case, using $\ell_d = \rho_e$ and $\eta = cst$, we got collapsed spectra $E(k)\rho_e \simeq (k\rho_e)^{-5/3}$ at MHD scales and $\simeq (k\rho_e)^{-2.8}$ at ion scales.

The transition between these two well-defined power-laws is found in the vicinity of the ion scales where the electron fluid has a significant drift with respect to the ion fluid and where fluctuations can be sensitive to the local plasma conditions [5–7]. This ion spectral break transition is not universal [8, 9].

At electron scales, the spectral shape is not yet completely established. Sahraoui et al. [4] show a clear spectral break at Doppler shifted ρ_e in the electron foreshock region. This suggests a possible cascade at scales smaller than ρ_e . Alexandrova et al. [3] show however that in the free solar wind a curved spectral shape is observed at these scales, instead of a break between two well defined power laws, suggesting dissipation of turbulence.

We present here a relatively large statistical study of 102 spectra measured by the Cluster mission [10] in the free solar wind. We find that their curved spectral shapes can be fitted by a unique function $\sim k^\alpha \exp(-k/k_0)$ in a range starting at the vicinity of the ion break point and extending beyond electron scales.

This result does not discard the possibility of another cascade at scales smaller than ρ_e , inaccessible with present instruments, but gives an increased strength to

*Electronic address: olga.alexandrova@obspm.fr; LESIA-Observatoire de Paris, CNRS, UPMC Université Paris 06, Université Paris-Diderot, 5 place J. Janssen, 92190 Meudon, France.

the hypothesis that at electron scales, i.e. at $\ell \sim 1$ km, there is dissipation of the electromagnetic turbulence in the solar wind. Whether this dissipation is final or only partial is still an open question.

The Cluster spacecraft was designed as a magnetospheric mission and its excursions in the solar wind not connected to the terrestrial bow-shock are rather limited in time. This is why it is difficult to find a large number of long time intervals to study the MHD inertial range. Nevertheless, time intervals of 10 minutes, as we will consider here, are frequent, and long enough to study kinetic scales.

We have selected homogeneous intervals among the first five years of the Cluster mission (2001-2005). In order to eliminate solar wind intervals when Cluster is magnetically connected to the Earth's bow-shock, we have used (i) electrostatic wave spectrograms, which show clearly waves typical of the electron foreshock and (ii) the connection depth, calculated with straight field lines and a paraboloidal shock model [11, 12]. When the interplanetary magnetic field \mathbf{B} is quasi-parallel to the solar wind velocity \mathbf{V} , Cluster is connected to the shock. Thus, our data set only contains intervals for which the angle Θ_{BV} between \mathbf{B} and \mathbf{V} is larger than 60° . If the turbulent fluctuations have a phase speeds $V_\phi \ll V$, we can detect by Doppler shift the fluctuations with $\mathbf{k} \parallel \mathbf{V}$. As \mathbf{B} and \mathbf{V} are quasi-perpendicular, this means that we mainly study fluctuations with $\mathbf{k} \perp \mathbf{B}$. We apply the Taylor hypothesis (i.e., the direct relationship between time τ and space scales $\ell = V\tau$) to get wave-number k from frequency f . However, about $\sim 10\%$ of the pre-selected intervals show the presence of right hand polarized whistlers in parallel propagation. For these waves the Taylor hypothesis is not applicable, because their $V_\phi > V$. We discard these intervals. This data selection process gives us 102 intervals.

In our statistical sample, the plasma conditions vary as usually in the free solar wind in fast and slow streams: bulk speed is $V \in [300, 700]$ km/s, ion temperature is $T_i \in [4, 80]$ eV, temperature ratio is $T_i/T_e \in [0.3, 5]$, mean magnetic field is $B \in [3, 20]$ nT, ion plasma beta is $\beta_i \in [0.1, 10]$, electron plasma beta is $\beta_e \in [0.1, 20]$, ion and electron temperature anisotropy T_\perp/T_\parallel are smaller than 1. As usual, the plasma parameters are inter-correlated: the strongest correlation is observed between V and T_i with a correlation coefficient of $C(V, T_i) \sim 0.8$, followed by the correlation between magnetic and ion thermal pressure, electron and ion temperatures, magnetic field intensity and electron temperature, $C(B^2, nkT_i) \sim C(T_i, T_e) \sim C(B, T_e) \sim 0.6$.

The Power Spectral Density (PSD) of magnetic fluctuations as a function of frequency in the spacecraft frame $P(f)$ is obtained from the STAFF instrument measurements [13] on Cluster. This instrument has two components: (1) The Search Coil sensors (SC), which measures magnetic waveforms at frequencies $f \in [0.1, 12.5]$ Hz in normal mode, and up to 180 Hz in burst mode; and (2) the Spectrum Analyser (SA), which measures mag-

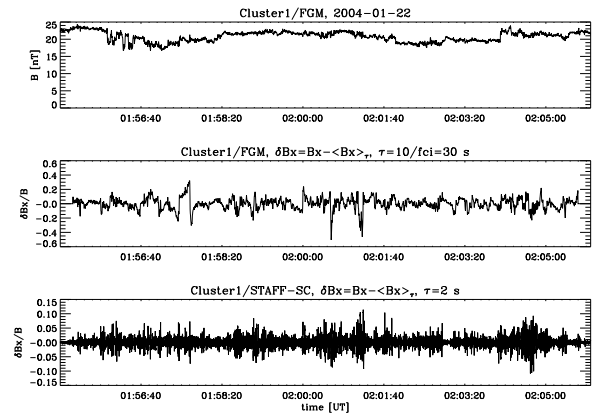


FIG. 1: Cluster/FGM & STAFF measurements in the solar wind on 22th of January 2004 (reference 10-minutes time interval, see text); (a) magnetic field modulus; (b) fluctuations $\delta B_x/B$ at scales smaller than $10/f_{ci} = 30$ s; (c) small scales fluctuations $\delta B_x/B$ within the $[0.5, 10]$ Hz frequency range.

netic and electric spectra from 8 Hz to 4 kHz every 4 s (so that for a 10 minutes interval there are 150 individual spectra). In this study we combine SC data in normal mode, and SA spectra for the frequencies where the Signal to Noise Ratio (SNR) is larger than 3. Note that measurements with $\text{SNR} \simeq 5 - 10$ are already affected by the instrumental noise, which becomes dominant for $\text{SNR} \sim 3$ [9]. This instrumental noise limit allows us to use SA-data up to 60 – 400 Hz as a function of the turbulence intensity (i.e., for the most intense spectrum, we have valid observations up to 400 Hz). A poor calibration of the first 3 frequencies of SA (at 8, 11 and 14 Hz) [Y. de Conchy and N. Cornilleau, private communication, 2011], was corrected by an interpolation of these points between the highest SC frequencies and the 4th and 5th points of SA spectra. The linear interpolation between $\log P(f)$ and $\log f$ is possible as far as the spectra follow a power-law at these frequencies.

Let us start with the most intense turbulent interval (called reference interval in the following), Figure 1. It lies in the free solar wind downstream of the interplanetary bow shock passed by Cluster at 01:35 UT on January 22, 2004. The mean field is very high, around 20 nT (top panel). In the two other panels we show magnetic field fluctuations δB_x at different scales τ : (i) FGM measurements of $\delta B_x = B_x - \langle B_x \rangle_\tau$ with $\tau = 10/f_{ci} \simeq 30$ s are within the Kolmogorov's inertial range; (ii) STAFF-SC data in the range $[0.5, 10]$ Hz, i.e., at frequencies higher than the ion spectral break (~ 0.3 Hz). One can see that within the inertial range, the relative amplitudes may be large, $\delta B_x/B \sim 0.5$.

For the analyzed time period, Figure 2 shows the PSD of magnetic fluctuations as a function of the wave-number $P(k) = P(f)V/2\pi$, which are determined using the Taylor hypothesis ($k = 2\pi f/V$) and the energy conservation law $\int P(k)dk = \int P(f)df$. Green crosses show the Morlet wavelet spectrum [14] of STAFF-SC measurements

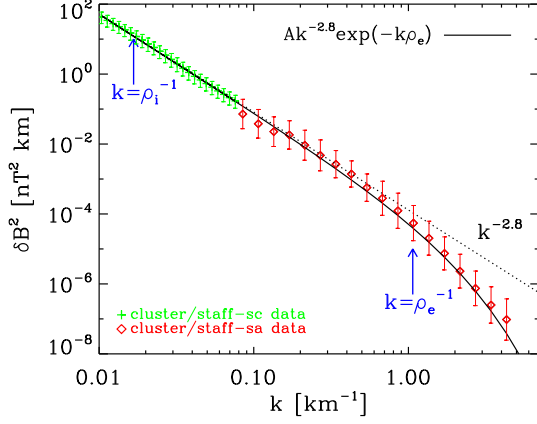


FIG. 2: Spectrum of magnetic fluctuations at scales smaller than 1000 km, measured by Cluster-1/STAFF on 22/01/2004 (reference spectrum, see text). Green crosses represent the SC measurements, red diamond show the SA measurements. The blue arrows indicate inverse ion and electron Larmor radii. Dotted line indicates the $k^{-2.8}$ power-law. The solid line gives the fluid-like dissipation law $Ak^{-2.8}\exp(-k\rho_e)$.

(presented in the bottom panel of Figure 1). Red diamonds display the STAFF-SA data for the same time period. (In this plot we keep the 3 first poorly calibrated data points, one can see them around $k = 0.1 \text{ km}^{-1}$ and compare with the result of the interpolation in Figure 3). The error bars are estimated from the variance of the PSD at each frequency [9]. This spectrum is valid up to $\simeq 400 \text{ Hz}$, which gives us the maximum wave-vector $k \sim 4 \text{ km}^{-1}$ (while $1/\rho_e \simeq 1 \text{ km}^{-1}$). This is the smallest scale ever measured with a good sensitivity at 1 AU in the solar wind.

From Figure 2 one can see that the two instruments are in agreement and that the high- k part displays a clear curvature. The curved spectrum makes one think of the high-wave number tail found in the 3D fluid turbulent cascade (e.g., Chen et al. [15]):

$$P(k) \sim k^\alpha \exp(ck/k_d) \quad (1)$$

where $k_d \sim 1/\ell_d$ is the dissipation wave number.

In [3] we have shown that the electron Larmor radius ρ_e can play the role of a dissipation scale ℓ_d in the collisionless solar wind, and that the quasi-universal spectrum between ion and electron scales follows a $k^{-2.8}$ power-law. Following this line, we plot $Ak^{-2.8}\exp(-k\rho_e)$ as a solid line in Figure 2. Only the amplitude A has been adjusted to the STAFF-SC (green) spectrum, the STAFF-SA measurements fall on this curve without any particular fitting. We plot as well the $k^{-2.8}$ power-law by a dotted line in order to underline the departure of the solar wind spectrum from the power-law shape.

Let us now check the generality of this findings, by considering the whole set of 102 spectra, presented in Figure 3. The top panel shows $P(f)$ -spectra, the reference

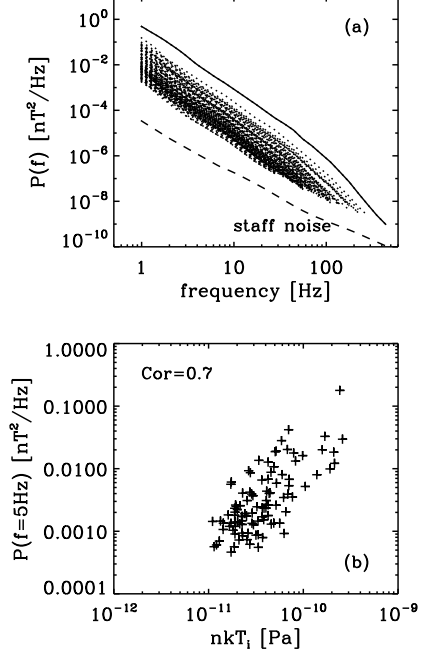


FIG. 3: (a) Raw 102 frequency spectra with signal to noise ratio greater than 3 measured by Cluster-1/STAFF in the free solar wind. The dashed line shows the instrument noise level. (b) PSD of magnetic fluctuations δB at a fixed frequency as a function of the ion thermal pressure in the solar wind, correlation coefficient is 0.7.

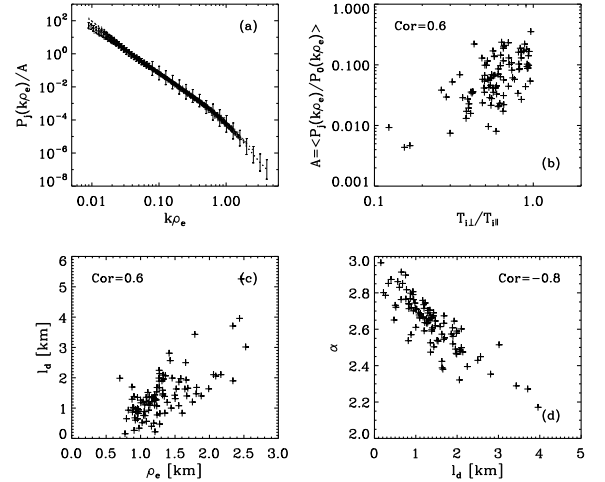


FIG. 4: (a) Normalized $P(k\rho_e)/A$ spectra; (b) A as a function of the ion temperature anisotropy, correlation of 0.64.

spectrum is presented by solid line, the other 101 spectra by dotted lines. The spectra look very similar: only their amplitude changes as a function of the solar wind pressures. The best correlation of the spectral intensity is found with the ion thermal pressure nkT_i , Figure 3(b). Similar result was found at MHD scales in [16].

The similarity of the $P(f)$ spectra suggests that there

is a quasi-universal spectrum such that any observed spectrum can be presented as a function of this universal spectrum with an appropriate rescaling [17].

Figure 4(a) shows the superposition of rescaled spectra $\tilde{P}(k\rho_e)/A$, where $P(k)dk = \tilde{P}(k\rho_e)d(k\rho_e)$ and A is the amplitude of the spectrum $\tilde{P}_j(k\rho_e)$ for a given period ($j = 1, \dots, 101$) relative to that of a reference period, \tilde{P}_0 , $A = \langle \tilde{P}_j(k\rho_e)/\tilde{P}_0(k\rho_e) \rangle$; $\langle \cdot \rangle$ denotes the average over the valid points of each \tilde{P}_j spectrum, but for f higher than a certain limit to avoid the range close to the ion spectral break, $f \geq 3$ Hz, corresponding to $k\rho_e \geq 0.02$. One can see that these spectra $\tilde{P}(k\rho_e)/A$ are superposed within the error-bars of the $\tilde{P}_0(k\rho_e)$ spectrum.

The normalized spectra $\tilde{P}(k\rho_e)$ no longer display the dependence on the ion thermal pressure, observed for the $P(f)$ -spectra. We find instead a new dependence, namely, on the ion temperature anisotropy, $A \sim (T_{i\perp}/T_{i\parallel})^{1.5}$, see Figure 4(b). The dependence between the turbulence intensity and $T_{i\perp}/T_{i\parallel}$ was observed for the ion break scale [5, 6]. Here we show that it keeps over smaller scales.

In order to specify the functional dependence of the observed spectrum, we perform a three-parameter fitting with equation (1), precisely with $P(k) = A_0 k^{-\alpha} \exp(-k\ell_d)$ with A_0 , α and ℓ_d as free parameters. This fitting gives the scale ℓ_d , that is correlated with $\rho_e \sim \sqrt{T_e}/B$ (see panel (c)), but not with $\lambda_e \sim 1/\sqrt{N}$ (not shown). This correlation between ρ_e and ℓ_d con-

firms our findings [3] on the rôle of ρ_e . The amplitude A_0 correlates, as expected, with A .

Last, the fitting process leads to a spectral index varying in the range $\alpha \in [2.2, 2.9]$ showing a nice anti-correlation with the dissipation scale ℓ_d , see Figure 4(d). Such an anti-correlation is indeed expected from a balance between energy injection and dissipation, with the dissipation scale going to zero when the spectral slope approaches the value 3 [18, 19].

If we summarize the findings of the present study, the dissipation range spectrum in a collisionless space plasma can be written as

$$P(k) = Ak^{-\alpha} \exp(-k\ell_d). \quad (2)$$

where A is related to the anisotropy of ions, $\ell_d \sim \rho_e$ and α is a function of the dissipation length.

This provides a unique description of the solar wind spectrum starting at ion scales and going beyond the electron scales, which is much more general than others proposed previously [3, 4]. The exponential tail of the spectrum indicates that the effective dissipation of magnetic fluctuations in the solar wind has a wave number dependence similar to that of the resistive term in collisional fluids $\sim \Delta \delta B \sim k^2 \delta B$. In the literature, there are several models of kinetic range of the solar wind turbulence (see e.g. [20–22]). However, none of them leads to the exponential tail found here.

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